

Chapter 2. Description of Stocks

2.1 Biological Information

Seven species of abalone are found in California:

- red abalone, *Haliotis rufescens*
- pink abalone, *H. corrugata*
- green abalone, *H. fulgens*
- black abalone, *H. cracherodii*
- white abalone, *H. sorenseni*
- pinto abalone, *H. kamtschatkana* (includes *H.k. assimilis* and *H.k. kamtschatkana*)
- flat abalone, *H. walallenis*

2.1.1 Geographic Range and Distribution

California abalone occur in coastal waters intertidally to 60 m (197 ft) in depth. Abalone are found in boulder and rock habitat, and are usually associated with kelp forests. Several species may be found occupying the same coastal regions, but are usually separated by depth. Red abalone occur along the entire California coastline (in appropriate habitat), while pink, green, and white abalones are associated with the warm, temperate waters south of Pt. Conception, Santa Barbara County. Black abalone occur from just north of San Francisco to Baja California, Mexico. The less common flat and pinto abalones are predominately found north of Point Conception, where water temperatures are generally cooler (Figure 1-2) (Cox 1960, Geiger 2000).

2.1.2 Reproduction

2.1.2.1 Maturation

Size at maturation varies among abalone species (Table 2-1). Abalone tend to mature earlier when food is plentiful.

2.1.2.2 Spawning and Fecundity

Abalone are broadcast spawners, releasing both eggs and sperm into the water during a synchronized event. Sex ratios are typically one to one. The spawning season varies among species (Table 2-2).

Broadcast spawners have high fecundity (a measure of the number of eggs and sperm produced by an individual) to compensate for the low probability of successful fertilization and high mortality of early life history stages. Abalone may produce only a few thousand eggs when they first spawn, but large adults can yield up to 23 million eggs. The number of eggs produced by a female increases with size. Fecundity in abalone can be affected by sea water temperature, the availability of food, and local environmental conditions.

A minimum density of spawners is essential for successful broadcast spawning. When populations drop below the minimum spawning density (also called minimum viable population size, or MVP), individuals are often too far apart to ensure successful reproduction (mixing of eggs and sperm). This phenomenon is referred to as the "Allee

effect”, and results in population declines and sometimes local extinction (Valiela 1984; Dennis 1989; Levitan *et al.* 1992). Because abalone are subject to the Allee effect, they are especially vulnerable to population collapse at low densities.

Table 2-1. Size and estimated age at maturity of California abalones. Age is derived from von Bertalanffy growth parameters, length infinity (L_{∞}) and the growth coefficient (k), as published in referenced papers.				
Species	Sexual maturity		Location	Reference
	(mm)	Years		
Red	♀40 ♂84	1+ 2+	California	Leet <i>et al.</i> 2001
Pink	40	1+-3	California	Parker <i>et al.</i> 1992
Pink	102-132*	2+	Mexico	Guzman-Del Proo <i>et al.</i> 1992
Green	60-70	1+ 1- 5	Catalina Is., California	Tutschulte and Connell 1988, Parker <i>et al.</i> 1992
Green	117-152*	2-5	Mexico	Guzman-Del Proo <i>et al.</i> 1992
Black	40, 44	2+	San Miguel Is., Pt. Arguello (mainland)	Leighton and Boolootian 1963, Parker <i>et al.</i> 1992, Haaker <i>et al.</i> 1995
White	♀88 ♂108	3	Coal Oil Point, Santa Barbara	Tutschulte 1976
Flat	not known	not known	not known	not known
Pinto	50	2+	Alaska	Woodby <i>et al.</i> 2000

* Average size at maturity

2.1.3 Recruitment

The term “recruitment” is used to define specific life-history stages, such as settlement of young-of-the-year abalone (less than 31 mm, or 1.1 in.), growth into reproductive sizes that contribute to spawning populations, and entry into the fishery. Although abalone produce large numbers of eggs and sperm, this does not guarantee reproductive success leading to recruitment. Studies throughout California have shown that successful recruitment occurs only occasionally (Tegner *et al.* 1989; Karpov *et al.* 1998). Reproductive success is dependent on oceanographic transport of larvae to suitable habitats, available settlement habitat, and levels of predation on post-larval and juvenile abalone.

Table 2-2. Biological information summary				
Species	Current Range	Depth	Spawning season	Foods
Red	southern Oregon to Baja California, Mexico (considered absent from southern California mainland)	intertidal to 24 m	N. CA: Oct. - Feb. S. CA: year-round	bull kelp, giant kelp <i>Laminaria</i> , <i>Egregia</i> , <i>Pterygophora</i> , <i>Ulva</i>
Pink	Pt. Conception to Baja California, Mexico	lower intertidal to 60 m	March - November	<i>Plocamium</i> , <i>Eisenia</i> , <i>Macrocystis</i> , <i>Dictyopteris</i>
Green	Pt. Conception to Baja California, Mexico	low tide line to 18 m	early summer to early fall	<i>Gelidium</i> , <i>Pterocladia</i> , <i>Plocamium</i> , <i>Gigartina</i> , red algae, bull kelp, giant kelp
Black	San Francisco Bay to Baja California, Mexico	intertidal	late spring and summer	giant kelp, <i>Egregia</i>
White	Pt. Conception to Baja California, Mexico	25 to 60 m	late winter to early spring	<i>Laminaria</i> , <i>Agarum fimbriatum</i>
Pinto	Alaska to Baja California, Mexico	Shallow water in north; deep colder water in south	April to June	small algae
Flat	Oregon to San Diego, California	6 to 21 m	not known	not known

2.1.4 Genetics

The ability to distinguish abalone populations on the basis of genetic characteristics is important for future abalone management. Genetic-based tools can be applied to identify stocks, assess recruitment success, assess population enhancement programs, and to support law enforcement in cases of poaching.

Hamm and Burton (2000) studied black abalone along the central California coast and found significant differences among seven locations. Genetic differences may arise because black abalone eggs, like pink and green abalone eggs (Tegner 1993), do not disperse great distances.

Kirby *et al.* (1998) identified genetic techniques which may be used to differentiate red abalone populations from different locations. Studies to date suggest stock differences among red abalone are minimal between northern and southern California (Kirby *et al.* 1998, Burton and Tegner 2000)

These genetic tools are useful in evaluating abalone out-planting techniques. For instance, Gaffney *et al.* (1996) suggested that an out-plant of red abalone conducted in the 1970s resulted in natural population enhancement, but a later genetic analysis (Burton and Tegner 2000) showed that there was no real effect.

2.1.5 Early Life History

2.1.5.1 Larval Development

Fertilized eggs hatch into free-swimming trochophore larvae within 24 hours. Larvae swim upwards in the water column initially (Crisp 1974), settling to the bottom as their shells develop (Forward *et al.* 1989). The rate of development in these non-feeding larvae is controlled primarily by temperature and varies from 4 to 15 days (Leighton 1972, 1974). Settlement marks the end of the larval phase and the beginning of the juvenile stage.

2.1.5.2 Larval Dispersal

The short duration of the free swimming larval phase (4-15 days) of abalone suggests that dispersal is limited (Tegner and Butler 1985, Prince *et al.* 1987). However, the occurrence of adults far removed from nursery habitat suggests that wide range dispersal does occur.

2.1.5.3 Post-larval Development

Abalone larvae in the wild settle and metamorphose into juvenile abalone primarily on crustose coralline algae, as do many other invertebrates (Saito 1981, Shepherd and Turner 1985, Kitting and Morse 1997). Newly settled abalone graze on the cuticle and epithelial contents of coralline algae (Garland *et al.* 1985). Sea urchins and other grazers maintain coralline substrates which in their absence become overgrown and unsuitable for juvenile abalone (Saito 1984, Shepherd and Turner 1985). Juveniles remain in coralline habitats until the abalone are about 6 mm (0.24 in.) in shell length. The post-larval stage is a critical stage in the life cycle, as over 90% mortality can occur at that time (Siquieros-Beltrones and Voltolina 2000). Sources of mortality may include poor substrate quality, physical displacement by wave action, incidental ingestion by large grazers, smothering by algae or detritus, genetic failure to fully metamorphose and begin feeding, and predation.

2.1.6 Age and Growth

Abalone are long-lived and can reach ages of 30 years or more. The growth rate varies among and within species, and with size and age. Variability also occurs on an annual as well as seasonal basis, and has been attributed to temperature, spawning cycle (seasonal gonad production), and fluctuations in food supply. Growth rates are rapid during the first 4 or 5 years, and slow thereafter. Table 2-3 provides estimates of age at the current and past recreational minimum legal size and at the past commercial minimum legal size. Despite the wide variability of growth rates some general trends are evident:

- Growth after the first year is irregular and varies according to the abundance and quality of food, location of the individual, and severity of competition.

- Abalone tend to grow comparatively quickly (given favorable conditions) until they reach sexual maturity; growth slows thereafter. The decrease in growth rate in mature abalone may be attributed to the shift in energy allocation from growth to gonadal production.
- Abalone tend to grow faster in areas with high food quality and quantity.

Table 2-3. Growth parameters of California abalones. MLS_R and MLS_C , are minimum legal size (mm) recreational and commercial, respectively. Years is the time it takes to attain those sizes. Data is derived from the von Bertalanffy growth parameters, length infinity (L_∞) and the growth coefficient (k), as published in referenced papers.

Species	MLS_R		MLS_C		Location	Reference
	(mm)	Years	(mm)	Years		
Red	178	6-12	198	8-15+	Santa Rosa Is.	Haaker <i>et al.</i> 1998
Red	178	12	198	---	North Coast	Tegner <i>et al.</i> 1989
Pink	153	14	159	16	Santa Catalina Island	Tutschulte 1976
Pink	152	4-9+	159	4-11+	Mexico	Guzman-Del Proo <i>et al.</i> 1992
Green	152	14-21	178	21	Catalina Is. California	Tutschulte and Connell 1988, Parker <i>et al.</i> 1992
Green	150	5-6	178	9-10+	Mexico	Guzman-Del Proo <i>et al.</i> 1992
Black	127	20 - 30	146	--	San Miguel Is., Pt. Arguello (mainland)	Parker <i>et al.</i> 1992, Haaker <i>et al.</i> 1995
White	?	?	?	?		
Flat	?	?	?	?		
Pinto	102	9	102	9	Alaska	Woodby <i>et al.</i> 2000

2.1.7 Food

Post-larval or early juvenile abalone feed mainly on bacteria, benthic diatoms, and single-celled algae that form a surface film on the coralline algae. Juvenile abalone eat coralline algae, and to a lesser degree brown, red, and green algae. Adult abalone consume most species of brown, red, and green algae, often in the form of unattached, drifting kelp. When drifting kelp is scarce, adult abalone feed on benthic diatom films.

In northern California, food is more limited during winter. During late fall, annual algae begin to disintegrate and perennial algae die back; hence food abundance drops sharply and remains low until spring. Among central and southern Californian giant kelp (*Macrocystis* spp.) forests however, die back events are not annual, and food is available all year.

2.1.8 Movement

Abalone are known to move during nocturnal feeding excursions (Bonnot 1948; Leighton 1968; Shepherd 1973), move seasonally in response to algal growth (Ault and DeMartini 1987), move from juvenile to adult habitat (Ault and DeMartini 1987), and move in response to predation (Donovan and Carefoot 1997). The amount of movement made by abalones depends on size, availability of food and shelter, and the type and degree of predation.

Ault and DeMartini (1987) observed a seasonal trend in red abalone movement from shallow water in spring to deep water in summer, and from deep water in fall to shallow water in winter in northern California. These movements by adult abalone were apparently in response to the highly seasonal and depth-limited abundance of the abalone's algal diet. Offshore movement at the start of the fishing season (April) could function to increase abalone density in the *de facto* deep water reserve which is inaccessible to the fishery. This movement pattern further supports the fishery closure in winter when abalone would be more vulnerable to fishing when they move to shallow water to access limited algal food resources.

2.1.9 Mortality

Sources of abalone mortality include natural and human-induced causes. Human-induced causes include fishing (Chapter 3), pollution, and impacts to habitat. Causes of natural mortality include predation, disease, and environmental factors.

2.1.9.1 Predation

Predation is a major cause of mortality in abalone populations. Vulnerability to predation is highest during the early life history stages (larvae and juveniles, for example), and decreases with size and age. The major non-human abalone predators in California are other invertebrates, sea otters, and fish.

Invertebrates

The most common invertebrate predators of abalone are sea stars, rock crabs, (*Cancer* spp.), and octopuses. Other known predators include the sheep crab, *Loxorhynchus grandis*; the California spiny lobster, *Panulirus interruptus*; Nuttall's hornmouth (snail), *Ceratostoma nuttalli*; and Kellett's whelk, *Kellettia kelletti*.

Fish

Fish predators of abalone include California sheephead, *Semicossyphus pulcher*; cabezon, *Scorpaenichthys marmoratus*; kelp greenling, *Hexagrammos decagrammus*; kelp bass, *Paralabrax clathratus*; moray eel, *Gymnothorax mordax*; bat rays, *Myliobatis californica*; and garibaldi, *Hypsypops rubicundus*. Larger adult abalone are less vulnerable to fish predation, unless they are injured or have become dislodged from the substrate.

Sea Otters

The influence of sea otter predation on abalone populations is so strong that sport and commercial abalone fisheries cannot co-exist with established sea otter populations (Wendell 1994, Watson 2000). In central California today, sea otters are the primary predator of subtidal adult abalone. Red and flat abalone co-exist with a re-established sea otter population off Hopkins Marine Laboratory in Monterey (Hines and Pearse 1982). High relief substrate in the area allows protection of abalone in crevices.

Prior to sea otter exploitation by humans, abalone and sea otters co-existed and shared a long evolutionary history during which abalone were at low densities within crevice habitats. Human exploitation caused the local extinction of the southern sea otter in most of its range in California. Large populations of abalone grew in the absence of sea otter predation. Remnant populations of sea otters along the central California coast increased during the period between 1914 and the mid-1970s at an annual rate of 4% to 5%. Thus, the sea otter population gradually expanded its density and range (Kenyon 1969; Miller *et al.* 1974; Geibel and Miller 1984).

The 1982 United States Fish and Wildlife Service (USFWS) sea otter recovery plan called for the translocation of sea otters to an area away from the central California coast: San Nicholas Island. This action, implemented in 1987, is now under review. Until completed, it is not clear whether the small colony at San Nicolas Island will be removed or allowed to grow naturally. Regardless, further expansion of the southern sea otter population is likely to occur. Abalone populations in southern California are so depleted that the addition of sea otters predation could pose a serious threat to the abalones' continued survival.

2.1.9.2 Diseases and Parasites

Withering Syndrome

A devastating disease known as Withering Syndrome (WS) has caused widespread declines among abalone populations (primarily black abalone) at the Channel Islands. WS has also been reported in red, pink, green and white abalones in captivity. Prior to the first reports of WS in 1985, abalone diseases were seldom reported (CDFG 1993a; Haaker *et al.* 1992).

Signs of WS include atrophy of foot muscle and gonadal tissues, emaciation, and lethargy. As abalone weaken, they lose their ability to cling to substrates and are easily dislodged and battered by waves, or eaten by predators and scavengers. WS is known to affect abalone of all sizes.

The causative agent of WS has recently been identified as an intracellular bacterium, *Candidatus xenohalotis californiensis* (Friedman *et al.* 2000, 2002; Moore *et al.* 2001). Transmission requires no intermediate host. In addition, the bacteria can survive in seawater for a limited period of time, and contact is not required for transmission to occur. Laboratory and field studies have shown a positive correlation between mortalities in WS-infected abalone and elevated water temperatures (Parker *et al.* 1992; Lafferty and Kuris 1993; Friedman *et al.* 1997; Moore *et al.* 2000).

Currently, both *Candidatus xenohaliotis californiensis* and the disease WS have been documented in abalone as far north as Point San Pedro (just south of San Francisco). The bacteria, but not signs of WS, have been observed at two locations north of San Francisco.

The specific effects of WS and the extent to which these effects are modulated by water temperature appear to vary between abalone species, but these differences are poorly understood. Nearly all studies have examined black or red abalone and information is lacking or mostly lacking for white, pink and green abalone. The effects of WS on each abalone species in the ARMP needs to be identified and considered in the implementation of recovery options.

Withering Syndrome may constitute a potentially serious and immediate threat to recovery of all species of abalone in southern California. Depending on potential long term environmental change, such as global warming, populations in central and northern California may also be adversely affected. Thus, WS has the potential of being a limiting factor in the present and future distribution of abalone populations in California.

The discovery of a few large (old) black abalone remaining in WS-affected areas suggests that a small percentage of the population may be naturally resistant to WS. If this resistance is found to be genetically-based, these animals could be employed as broodstock to propagate WS-resistant black abalone.

Sabellid Polychaetes

The California abalone aquaculture industry has been working to rid itself of a parasitic sabellid polychaete, *Terebella heterouncinata*, following its inadvertent introduction from South Africa in the late 1980s. This worm lives on the growing edge of abalone shells. Heavy infestations cause disruption in normal shell growth, resulting in deformed, slow-growing, brittle shells.

The State and industry have acted to keep this worm from infesting native mollusc populations by prohibiting the movement or placement of cultured abalone into state waters. The cooperative containment and eradication efforts appear to have confined sabellids to one location in the wild near one aquaculture outfall. Removal of infested wild molluscs may have successfully eradicated this introduction. The Department will continue to allow out-planting of abalone only from facilities certified as sabellid-free.

Shell-boring Organisms

Cliona celata californiana is a boring sponge that secretes an acidic substance etching tiny holes in the abalone shell's surface. A heavy infestation of boring sponges weakens the shell and increases the likelihood of shell damage and death (MacGinitie and MacGinitie 1949; Cox 1962; Hansen 1970). Piddock clams, *Penitella conradi*, and date mussels, *Lithophaga subula*, are boring bivalve molluscs. The piddock clam drills at right angles to the shell's surface, whereas the date mussel secretes acid to dissolve a hole in the shell and may enter at an acute angle. Where boring molluscs are abundant, abalone may have many thickened blister areas in their shell and may

succumb to boring molluscs (Cox 1962; Hansen 1970). Polydorid polychaetes burrow into abalone shells primarily around the protoconch (Hansen 1970). Severe infestations can inhibit growth (Hahn 1989) and promote the formation of distorted, dome-like shells. *Polydora websterii* has been identified as a symbiont of cultured red abalone (McMullen and Thompson 1989). This species is not known to deform shells in wild populations.

2.1.9.3 Environmental Factors

Other sources of natural mortality include environmental factors such as storms (including wave stress, boulder movement and sand scour), increased water temperature, oxygen depletion, salinity variations, and toxic chemicals.

El Niño Events

El Niño/Southern Oscillation (ENSO) climate anomalies occur when the ocean-atmospheric system in the tropical Pacific is disrupted, affecting weather patterns over much of the globe. ENSOs are characterized by heavy rainfall, monsoons, and warm sea-surface temperatures. Along the coast of California, ENSOs depress the thermocline (a temperature differential in the water) and diminish the California Current. Depression of the thermocline away from the upper surface layer reduces primary productivity and adversely affects the food chain in coastal upwelling ecosystems. ENSO-related storms cause mass mortalities of kelp species such as giant kelp, an important abalone food item.

Large-scale disturbances of kelp populations from ENSOs and severe storms seem to follow a regular pattern of occurrence. ENSOs occur every 2 to 10 years. These events are a normal part of the ecosystem, and species have developed strategies that allow them to recover under natural conditions. However, a species' resiliency may be diminished if the species is also subject to fishing and/or if the event is particularly severe or prolonged. Since 1977, the frequency, duration, and intensity of warm-water ENSOs has increased. This prolonged period of greatly-increased environmental variability on a decadal scale may have contributed to the steady decline of abalone populations in southern California (Tegner *et al.* 2001).

Because kelp forest communities are vital to abalone populations, any event that reduces the productivity of these communities may indirectly affect the abalone populations associated with them. ENSOs diminish or even exhaust abalone food supplies by inhibiting the production of kelp and other algae. When food is limited, abalone are at a great competitive disadvantage because they are sedentary, passive feeders. In addition to reducing the quantity and quality of the drift kelp that abalone consume, ENSOs may alter current patterns and thus affect larval dispersal. Also, violent wave action from El Niño storms can kill abalone directly by crushing them during boulder movement or by covering abalones' rocky habitat with sand. Warm water conditions also exacerbate the debilitating effects of WS (Friedman personal communication).

2.1.10 Competition

Sea urchins are major competitors of abalones (Leighton 1968; Shepherd 1973b; Tegner and Levin 1982; Tegner 1989a). The red sea urchin, *Strongylocentrotus franciscanus*, and the purple sea urchin, *S. purpuratus*, directly compete for food and space with abalones in California. Both abalones and sea urchins feed on drift kelp. Following their release from sea otter predation, invertebrate grazers such as abalones and sea urchins flourished in nearshore waters for nearly a century in southern California (Tegner 1989a, 1989b). During most of this time, the supply of drift algae remained relatively abundant and predictable (Wilson and McPeak 1983). In this alternate, stable state, abalones maintained spatial dominance over sea urchins and abalone stocks increased. Since heavy exploitation of these accumulated abalone stocks began in the mid-1940s, the equilibrium has shifted in favor of sea urchins (Tegner 1989a). In northern California large scale commercial take of red sea urchin beginning in 1985 may have increased kelp production and freed space thus benefitting red abalone populations (Karpov *et al.* 2001). Selective harvesting of abalones releases sea urchins from interference competition and tends to accelerate the displacement of abalones by sea urchins (North and Pearse 1970; Shepherd 1973b). In addition, if drift algae becomes limiting, sea urchins can reduce the algal resource to a level below that necessary to maintain abalones (Tegner 1980, 1989a). Sea urchins are adapted to survive in heavily-grazed habitats because, unlike abalone, they have alternate methods of obtaining sustenance (Cox 1962). They actively seek attached kelp, whereas abalones remain in place and passively wait for food to drift their way (Shepherd 1973b; Tegner 1980). Where few predators are present to keep sea urchin populations in check, sea urchins can form massive feeding fronts. Motile aggregations of sea urchins can destroy kelp forests by eating almost all the macroalgae in their path (Tegner 1980, 1989a; CDFG CEQA Document 1993). In addition, sea urchins may inhibit kelp recruitment by over-grazing rock surfaces to such an extent that new algal spores cannot attach to the bare rock (Leighton 1966, 1968, 1971; Dean *et al.* 1984; Dayton and Tegner 1989).

Lack of space is the primary cause of competition between different species of abalone (intraspecific competition). Competition between abalone species is reduced by separation of species into different depth ranges and temperature regimes.

2.1.11 Community Associates of Abalone

Abalones live on intertidal and subtidal rocky substrate. Depending on the species, the habitat may include bare rock, surf grass, kelp forest, or deep sub-canopy-forming kelps. These communities are complex systems where biological and environmental factors interact. Biological interactions include competition within and among species, predator/prey interactions, disease, and parasite/host interactions. Ocean conditions have been found to shape the dynamics which influence abalone populations (Dayton and Tegner 1984). Kelp forest community dynamics for some abalones are further confounded by human activities such as fishing (Tegner and Dayton 2000) and pollution.

Subtidal abalone are typically closely associated with kelps which provide food and shelter. Factors that impact kelp abundance may in turn also affect abalone

populations. For example, storms can severely reduce kelp beds, thus reducing growth and reproduction. In southern California, giant kelp may be adversely affected by warm, low-nutrient water from El Niño events which may not support kelp maintenance and growth (Gerard 1976; Dayton and Tegner 1984). During El Niño years, red abalone growth rates were reduced (Haaker *et al.* 1998) and reproduction was diminished (Tegner *et al.* 1989; Tegner *et al.* 2001). In northern California, growth and reproduction is linked to seasonal kelp productivity and abundance (Giorgi and DeMartini 1977).

Predator-prey relationships are an important factor defining abalone abundance and distribution. For instance, the sea otter is an important predator that has large direct impacts on abalones (Ebert 1968). Where abalones and sea otters co-occur, abalone populations are restricted to small sizes and cryptic habitat (Hines and Pearse, 1982). Where sea otters are absent, an alternative predator-prey relationship occurs, in which herbivores, including abalones, are larger and occupy a less restricted distribution.

Other predator-prey relationships have indirect effects on the kelp community which can affect important to abalones. Sea otters also prey upon other herbivores, such as sea urchins (Estes and Palmisano 1974; Duggins 1980, VanBlaricom and Estes 1988), which compete with abalones for food and space. Sea otters also prey on sea stars, octopuses, and crabs, which all feed on small abalones.

Competition among species is another important factor that shapes abalone populations. The primary abalone competitor is the sea urchin (Section 2.1.10). Adult sea urchins and abalone both eat kelp and therefore may compete particularly when kelp resources are limited (Tegner and Levin 1982; Karpov *et al.* 2001). While adult red abalone and red sea urchins may compete for space (Deacon 1977; Karpov *et al.* 2001), at other life stages they may share a beneficial relationship. Juvenile abalone have been shown to shelter under the spine canopy of adult red sea urchins (Ebert 1968; Tegner and Dayton 1977). In northern California, areas with red sea urchins have significantly more juvenile red and flat abalone than areas where sea urchins had been fished (Rogers-Bennett and Pearse 2001). Sea urchins appear to be critical for the survival of small abalone in the 5-20 mm size class in California (Rogers-Bennett and Pearse 2001) and elsewhere (Kojima 1981; Tarr *et al.* 1996; Day and Branch 2002). Sea urchins may also maintain coralline algal pavements appropriate for juvenile abalone settlement (Saito 1981). Although the commercial harvest of sea urchins may reduce competition between adult abalone and sea urchins for kelp resources, it is likely that sea urchin fishing exposes juvenile abalone to predation (Tegner *et al.* 1989). If so, then the sea urchin fishery in southern California may have contributed to recruitment failure in abalone populations by reducing the available habitat for juveniles (Tegner and Dayton 2000).

Ocean conditions which include severe storms, El Niño events, and upwelling can alter abalone population structure. Severe storms and associated wave action are highly disruptive to community structure, through wave-caused rock movement and sand transport, and reduction of food algae. El Niño events can affect abalone growth and reproduction. Upwelling benefits populations by increasing nutrient flow and decreasing water temperatures, which are beneficial for kelp growth.

Ocean conditions may affect other abalone-associated species in a way that could affect abalones. Ocean conditions may drive sea urchin recruitment events such that during El Niño years when there is a relaxation of offshore advection of surface waters, larvae are retained and settle nearshore (Ebert *et al.* 1999). After they grow to adulthood, these large, El Niño year classes of sea urchins may dominate kelp communities (in the absence of human fishing and sea otters). When sea urchin densities are high, storm-related destruction of kelp beds and subsequent food shortages are thought to trigger a switch in grazing patterns from drift kelp feeders residing in crevices to destructive grazers that mow down kelp beds creating barren areas (Harrold and Pearse 1987) thus increasing competition with abalones. Storms can also reverse the structure of these barrens communities back to kelp forests by eliminating sea urchin aggregations and clearing rock for kelp settlement and re-establishment (Ebeling *et al.* 1985) which would tend to ease competition with abalone.

2.1.12 Abalone Habitat

There are three main habitat types in California: intertidal, subtidal kelp bed, and deep water. The type and availability of abalone habitat varies between northern, central, and southern California. Regardless of habitat type or location, abalone require hard substrate (bedrock, boulders, shale shelves, and rock piles) for attachment.

2.1.12.1 Habitat Types

Intertidal Habitat

Intertidal rocky substrate is a significant habitat type for southern black and green abalones and northern red abalone. Intertidal habitats are subject to long periods of desiccation, high temperatures, intense light, and high wave stress during low tide. The stability of intertidal habitats depends on the extent of rocky substrate, frequency of disturbances, and the presence of loose sand and rock.

Subtidal Kelp Bed Habitat

Subtidal kelp bed areas form the primary habitat of all California abalone species. Kelp beds occur on rocky substrates needed for abalone habitat, and kelp is a major food source of abalones. Kelp beds occur in cool (< 20°C), nutrient-rich upwelling areas (Foster and Schiel 1985). Annual kelp, *Nereocystis luetkeana*, dominates in northern California and perennial kelps *Macrocystis integrifolia* and *Macrocystis pyrifera* dominate in central and southern California.

Deep Water Habitat

Deep water abalone habitat is rocky substrate deeper than 24 m (80 ft). Of the seven California abalone species, only the white abalone uses deep water rocky substrate as its primary habitat, and can be found at depths greater than 60 m (200 ft). However, red abalone have been seen as deep as 30 m (100 ft) and pink abalone can be found as deep as 36 m (120 ft). Food availability is limited within deep water habitat,

as kelp forest are restricted to shallower depths. Some deep offshore reefs may support local kelp beds. Several species of deep water brown alga are found on deep reefs off southern California, including *Laminaria* sp., *Agarum* sp., and *Pelagophycus* sp. Several of these algae form significant sub-canopies over deep rocky substrate, and provide food to deep-dwelling herbivores.

2.1.12.2 Latitudinal Habitat Variation

Northern California

The northern California coastline is characterized by steep slopes which provide less habitat for abalone than the broader shelves found in central and southern California. Water temperature in northern and central California is cool, typically 8-15°C (46-59°F). This allows red abalone to occupy shallower depths [from low intertidal to 6 m (20 ft)], than in southern California. Bull kelp, *N. luetkeana*, is the dominant algal species.

Not all northern California rocky shores are suitable habitat for red abalone. Most of Del Norte and Humboldt Counties have very few red abalone despite abundant rocky shores. Several factors may limit abalone populations in these counties including increased amounts of fresh water, turbidity (which limits algal growth by decreasing light penetration), and sedimentation from large rivers. These shores are also more exposed to storm waves and have few of the surge channels that abalone favor.

Central California

Central California has extensive rugose, rocky habitat and high kelp productivity making it ideal for abalone. Temperatures typically range from 10 to 15°C (50 to 59°F). Central California is dominated by *M. pyrifera*, an annual kelp.

Southern California

Southern California has areas of gently-sloping rocky shores which are favorable for abalone. The northern Channel Islands (San Miguel, Santa Rosa, Santa Cruz, and Anacapa) help protect much of the mainland from the northwest winds and swells generated by storms to the north. Water temperatures range from 15 to 21°C (59 to 70°F), which is in the optimal temperature range for growth of juvenile red abalone (Leighton 1974). Southern California kelp forests are dominated by *M. pyrifera*.

2.2 Status of Abalone Stocks

The status of California abalone ranges from near extinction (white abalone) to fairly robust populations (northern California red abalone). Status of the stocks also varies with location. The status of each abalone species is discussed below.

2.2.1 Red Abalone

2.2.1.1 Northern California Stocks

Northern California red abalone populations continue to support a viable fishery, but population and fishery data analyzed in 2001 revealed four trends which are cause for concern:

Concentration of Fishery Effort and Increased Take

Average take and effort estimates for 1998-2000 have increased compared to estimates for 1983-1989, and there has been a substantial concentration of fishery effort in Sonoma and Mendocino Counties. This effort shift has been accompanied by an estimated 25% increase in take. When poaching estimates of 217,000 lb [98 metric tons (t)] are added to the estimated recreational take, the total take exceeds 1.7 million lb (771 t). This level of take approaches the average red abalone harvest in southern California that was unsustainable and preceded fishery collapse (Karpov *et al.* 2000).

Evidence of Poor Recruitment

Recruitment is necessary to ensure replacement of animals removed by the fishery. Recruitment of juvenile abalone measuring less than 30 mm (1.2 in.) is indicative of successful reproduction, while recruitment of high densities of emergent (non-hidden) abalone measuring 100 to 178 mm (4 to 7 in.) is predictive of increases in fishable populations (Karpov *et al.* 1998).

Recruitment to the adult population occurs after successful larval settlement and metamorphosis, and development as juveniles (Tegner *et al.* 1989). Under optimal conditions, recruitment of abalone can be high. High fecundity and local dispersion appear to favor successful juvenile recruitment (Shepherd and Turner 1985, McShane 1992). However, most of the time, recruitment is highly variable regardless of adult abundance. Evidence based on a long time series in northern California suggest that successful year classes occur infrequently (Karpov *et al.* 1998, 2001). Large numbers of abalone smaller than 100 mm (4 in.) were last observed between 1986 and 1992 at Van Damme State Park in Mendocino County (Karpov *et al.* 1998). Since 1992, the abundance of abalone between 50 and 125 mm (2 and 5 in.) has declined substantially at this location (Figure 2-1)(Karpov *et al.* 2001). Recent surveys at four other northern coastal sites (Point Cabrillo Marine Reserve in Mendocino County, and Bodega Bay Marine Reserve, Salt Point State Park, and Fort Ross State Park in Sonoma County), revealed few young-of-the-year and emergent recruits, with young-of-the-year least abundant in Sonoma County (Table 2-4). This lack of sub-legal animals suggests poor recruitment over the last decade. Given the slow growth rates of abalone, a successful spawn in any year would not reach the sport legal size of 178 mm (7 in.) for over a decade.

Declines in Deep Water Stocks

The prohibition of the use of scuba and surface-supplied air while taking abalone establishes a depth refuge for a portion of the stock, because free divers generally cannot dive deeper than 8.5 m (28 ft). However, declines in deep-water stocks are evident between 1986 and 1999 at one of four sites examined (Karpov *et al.* 2001). Decreases in deep stocks suggest that “refuge by depth” is not protecting as many abalone as in previous years, leaving the population vulnerable to overfishing.

Spatial Depletion

Catch and effort creel data provide evidence for serial depletion by area at heavily-fished sites, with increased take of abalone from deeper water and from more remote locations and a decline in the number of abalone taken per trip. At Moat Creek in Mendocino County, the distance of travel from access points to take locations doubled for shore-pickers between 1989-1994 and 1995-2000. Aerial surveys between 1975 and 1985 showed that there has been a significant decline in the number of shore-pickers, while diving effort increased significantly. This could represent a shift from intertidal to subtidal fishing as nearshore stocks become depleted.

2.2.1.2 Central and Southern California Stocks

Based on long-term studies, the overall trend in red abalone abundance is one of decline in all locations surveyed (Figure 2-2) (Karpov *et al.* 2000).

Stocks in key areas in southern California (Santa Rosa Island, Santa Cruz Island, and the California mainland) appear to have been extirpated, with remnant stocks showing little evidence of recovery. The trend in red abalone abundance and density (determined from long-term studies conducted by the Department and the Channel Islands National Park) is one of decline at all locations surveyed, except for San Miguel Island where red abalone populations appear to be stable (Karpov *et al.* 2000). During the most recent Department research cruise (2001), red abalone abundance (measured as the number of abalone encountered by one diver per hour) at Santa Rosa and Santa Cruz Islands was found to range from 0 to 7.6 abalone, and 0 to 1.4 abalone respectively. San Miguel Island is the only location that has a minimum viable population size. However, even at the close of the San Miguel Island fishery, the proportion of the population that was larger than commercial legal size (198 mm; 7.75 in.) was low, indicating that legal-sized stocks had been severely depleted.

In areas of central California repopulated by sea otters, Wendell (1994) showed that the estimated red abalone population size decreased by 84% within 6 years following the re-introduction of sea otters. Due to the high amount of crevice-type habitat, populations stabilized at these low levels (7% of the initial 1965 estimate) (Wendell 1994). Hines and Pearse (1982) showed that abalone populations in otter areas are sustainable at low levels, but with a reduced average size of 75 mm (3 in.), half that of abalone in non-otter areas. Although stable, these populations do not provide fishable stocks.

North of the sea otter range in central California and at the Farallon Islands, evidence suggests that abalone stocks are depressed. In a dive survey at Fitzgerald

Marine Reserve (San Mateo County) in central California, Karpov *et al.* (1997) found densities of red abalone of $0.02 /m^2$, which is 1/10 of the lowest density found in heavily fished areas off northern California by Parker *et al.* (1988). At the Farallon Islands, the Department conducted a remotely-operated vehicle (ROV) survey in 2000 that targeted areas of historic high abalone abundance (based on commercial diver observations). Preliminary results indicate that abalone densities were below $0.02 /m^2$.

2.2.2 Pink Abalone

The pink abalone was once a common species in southern California. The Department's historical commercial landing records for pink abalone show a peak in 1952 at almost 1508 t (3,325,000 lb) and a decline thereafter to 7 t (15,400 lb) in 1994.

Study sites in the Channel Islands provide the best recent data on pink abalone populations. Pink abalone abundances have shown tremendous declines in the Channel Islands since 1985. Anacapa Island has the highest number of pink abalone of the five islands monitored.

2.2.3 Green Abalone

Now rare, the green abalone was once a common species in southern California, and was historically abundant in the warmer parts of the Southern California Bight (Cortez Bank, along the mainland from the Palos Verdes Peninsula south, and San Clemente, Santa Catalina, and Santa Barbara Islands) (Tegner and Butler 1985a). The Department's historical commercial landing data for green abalone peaked at 510 t (1,125,000 lb) in 1971 and thereafter plunged precipitously to a low of 0.72 t (1,600 lb) in 1995.

The Department conducted research cruises off San Clemente and Santa Catalina Islands from 1995 to 1999 and in 2001 to survey green abalone. Green abalone were rare at these sites, with densities ranging from 0 to less than 40 ab/ha ($0.004/m^2$).

2.2.4 Black Abalone

Now a rare species, the black abalone was abundant in California until the mid-1980s; it once occurred in such high concentrations that individuals were observed stacking on top of one another.

Density studies of black abalone at four of the Channel Islands (San Miguel, Santa Rosa, Anacapa, and Santa Barbara Islands) since the early 1980s show population declines attributed to WS. In the vicinity of Point Conception, Santa Barbara County, black abalone populations exhibited mortalities of 39% to 97%. At Point Arguello, Santa Barbara County, densities increased from 1992 to late 1993; however, after WS was first observed in 1994, densities started to decline and remained at a low level (1,000 ab/ha, or $0.1/m^2$) through November 2000. Densities have now increased to 2,500 ab/ha ($0.25/m^2$) (CDFG unpublished data), but this is far lower than historic population levels of up to 1,000,000 ab/ha ($100/m^2$) (Davis 1993).

Table 2-4. Red abalone population survey at Van Damme, Fort Ross and Salt Point State Parks, 1986-2000

		Van Damme SP				Fort Ross SP		Salt Point SP	
		1986	1989	1992	1999	1986	1999/00	1986	2000
Emergent	Shallow (<28 ft.)								
	Density (#/m ²)	0.37	0.89	0.76	1.04	0.41	0.58	0.73	1.27
Legals	>175 mm (6.9 in.)	55.3%	24.9%	22.1%	48.4%	69.3%	66.4%		66.7%
Sublegals	<175 mm (6.9 in.)	44.7%	75.1%	77.9%	51.6%	30.7%	33.6%		33.3%
Juveniles	>50 and <125mm (2.0 in & 4.9 in.)	8.2%	29.6%	17.2%	9.8%	0.5%	1.9%		5.9%
Invasive	<50 mm (2.0 in.)	*	*	16.8%	6.2%	*	0.0%	*	2.0%
Emergent	Deep (<28 ft.)								
	Density (#/m ²)	0.14	0.3	0.85	0.14	0.04	0.33	0.29	0.52
Legals	>175 mm (6.9 in.)	76.1%	61.1%	50.2%	61.9%	63.6%	67.9%		78.6%
Sublegals	<175 mm (6.9 in.)	33.9%	38.9%	49.8%	38.1%	36.4%	32.1%		21.4%
Juveniles	>50 and <125mm (2.0 in & 4.9 in.)	2.2%	12.2%	12.3%	1.9%	2.3%	0.0%		0.0%
Invasive	<50 mm (2.0 in.)	*	*			*	4.6%	—	7.1%

* No invasive surveys conducted in 1986-1999, 1992-1990. Van Damme State Park combined shallow and deep.

2.2.5 White Abalone

On 29 May 2001, the National Marine Fisheries Service listed the white abalone as an endangered species under the federal Endangered Species Act (ESA), making this the first marine invertebrate to be listed due to direct human take (Hobday and Tegner 2000). Current population estimates indicate that white abalone may have declined by as much as 99% compared to 25 years ago. An abundance estimate based on deep survey data from 1997 (Davis *et al.* 1998) was 1,600 animals (Hobday and Tegner 2000).

In comparison, a conservative estimate of baseline white abalone population abundance using commercial landings data from 1969 to 1978 is 363,000 animals (Hobday and Tegner 2000). This abundance estimate suggests that the white abalone density in 1969 was approximately 500 ab/ha (0.05 /m²), assuming no new individuals entered the population during the 10 yr peak of the fishery for this species. Remnant populations of adult white abalone remain mostly at depths of greater than 33 m (108 ft), in the deepest portions of their former distribution. Their distribution may be further

limited to a narrow strip of habitat along the rock/sand interface of isolated boulders at depth. This may be problematic for population recovery since temperatures at these depths may be unsuitable for larvae. Modern biomass and egg production estimates are also very low (Rogers-Bennett personal communication).

Despite the closure of the white abalone fishery in 1996, the remaining population may not recover on its own due to natural mortality (primarily predation and old age), and because individual white abalone may be too far apart to ensure successful reproduction (severe Allee effect). Low breeding density and reproductive failure suggest that recovery without significant human intervention is unlikely. A captive breeding program is now underway; in 1999, 18 adult broodstock were collected and brought into two culturing facilities. Three of these animals have been successfully spawned, producing more than 100,000 juveniles (McCormick personal communication). The disposition of these abalone will require a comprehensive evaluation, addressing the genetic and disease implications, size, and location of out-planting. Currently there is a prohibition on out-planting abalone to the natural environment from facilities not certified sabellid (worm)-free. As a listed species, white abalone recovery is managed by the National Marine Fisheries Service with the assistance of a white abalone recovery team which includes members from the Department.

2.2.6 Pinto Abalone

Pinto abalone were more common in northern California in the 1970s when they made up 13% of the abalone population (Gotshall *et al.* 1974). Today they are very rare throughout northern California, making up <1% of the population (Rogers-Bennett *et al.* 2002). Cox (1962) reported that large numbers could occasionally be found in deeper waters. This species was not a major component of the California commercial or recreational catch.

2.2.7 Flat Abalone

Flat abalone have always been rare throughout their range in California (McMillen and Phillips 1974). Few studies have documented the abundance of flat abalone, and little is known about this species. In central California, abundances within the range of the sea otter appeared to have declined steadily since the 1970s when flat abalone made up 31% to 38% of abalone populations (Lowry and Pearse 1973; Cooper *et al.* 1977). Recent surveys revealed that flat abalone comprised only 5% of the total population, which is now dominated by red abalone in deep crevice habitat (Rogers-Bennett *et al.* 2002). In northern California, flat abalone have always been rare, making up less than 5% of the population (Gotshall *et al.* 1974; Rogers-Bennett and Pearse 1998). Due to their small size, flat abalone are not usually targeted by the recreational fishery.